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Book of Abstracts
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Kellie Ann Beall, Editor

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U.S. Department of Commerce
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Brand Propagation of Post-Earthquake Fires

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Fires following earthquakes are a serious problem due to multiple simultaneous ignitions. The difficulties are exacerbated by brand propagation, where burning particles are deposited downwind from large, post-earthquake fires. Calm winds after the 1989 Loma Prieta, 1994 Northridge, and 1995 Kobe earthquakes reduced the effect of fire spread by brand propagation; it is unlikely that future earthquakes will be so conveniently correlated with the weather. This research is intended to optimize limited resources by quantifying the effects of wind speed and particle shape on the maximum brand propagation distance from large, post-earthquake fires.

Post-earthquake fire growth by remote spotting can be decomposed into three sequential events[1]: lofting, propagation, and downwind burnout or deposition with possible fire initiation. The dimensionless equations for spherical, cylindrical, or disk-shaped brands during the first two phases [2][3] are

$$\frac{dV_x^*}{dt^*} = \frac{\|W^*\|W_x^*}{L^*} - \frac{V_x^*}{m^*}\left(\frac{dm^*}{dt^*}\right)$$
$$\frac{dV_z^*}{dt^*} = \frac{\|W^*\|W_z^*}{L^*} - \frac{V_z^*}{m^*}\left(\frac{dm^*}{dt^*}\right) - 1 \qquad (1)$$

where the symbols are defined in the notation and the average ambient wind is assumed to be aligned with the x-axis. Note that the non-dimensional length scale, L^*, absorbs the shape-dependent aspects of the acceleration due to drag. The drag coefficient is assumed to be constant, with $C_d = 0.45$, 1.2, and 1.17 for $100 < Re < 2 \times 10^5$ for the three shapes. Eqs. (1) are coupled with the position equations, $dx^*/dt^* = V_x^*$ and $dz^*/dt^* = V_z^*$, and with an equation for the temporal mass change that is shape- and orientation-dependent to provide a closed set of equations for the brand lofting and propagation. Combustion rates for constant-density brands have been determined for spheres and for disks -- oriented perpendicular to the relative velocity -- as follows

$$\frac{1}{m^*}\left(\frac{dm^*}{dt^*}\right) = -\frac{3}{\Phi L^*} \qquad \text{sphere}$$
$$\frac{1}{m^*}\left(\frac{dm^*}{dt^*}\right) = -\Psi\left(\frac{W^*}{L_o^*}\right)^{1/2} \qquad \text{disk} \qquad (2)$$

with $\Phi = \left(\frac{9}{64}\right)\left(\frac{\rho_a}{\rho_s}\right)\left(\frac{C_d^2}{\alpha \ln(1+B)}\right)\left(\frac{\dot{Q}_o\sqrt[3]{g}}{\rho_a c_p T_o}\right)^{3/5}$, $L_{c,\,sphere} = (3/4)(z_c C_d)(\rho_a/\rho_s)$,

$L_{c,\,disk} = (3/4)(z_c C_d)(\rho_a/\rho_s)$, and $\Psi = \left(\frac{32}{3}\right)\left(\frac{\nu g \varepsilon \rho_s}{\rho_a C_d^3 V_c^3}\right)^{1/2}(0.353 r^{-0.02} B^{0.611 - 0.0651\ln(B)}))$, so that

$L_{c,\,sphere} = (3/2)\, L_{c,\,disk}$. The combustion rate for spheres is based on the burning droplet model, while that for disks is derived from stagnation-point burning.

The flow field is divided into a Baum and McCaffrey plume [4] ($V_c = ((\dot{Q}_o g^2)/(\rho_a c_p T_o))^{1/5}$ and $z_c = (\dot{Q}_o/((\rho_a c_p T_o)\sqrt{g}))^{2/5}$), lofting the brand, and a constant horizontal wind, pushing the particle downstream. The ALOFT large eddy simulation will replace these approximations during the current grant period. Brands are removed from the plume and propagated such that the maximum downwind distance is realized; a brand with higher loft will burn out above the ground, while one that is removed earlier will not propagate the maximum distance.

Disk brands that are tilted about an axis of symmetry at an angle of attack γ, which is positive CCW, have a lift force acting perpendicular to that of drag. The acceleration due to drag in Eqs. (1), $\|W^*\| W^*_{x,z}/L^*$, is modified to include lift,

$$\frac{dV^*_x}{dt^*} = \frac{\|W^*\|}{L^*}(W^*_x \cos(\gamma) - W^*_z \sin(\gamma)) - \frac{V^*_x}{m^*}\left(\frac{dm^*}{dt^*}\right)$$
$$\frac{dV^*_z}{dt^*} = \frac{\|W^*\|}{L^*}(W^*_z \cos(\gamma) + W^*_x \sin(\gamma)) - \frac{V^*_z}{m^*}\left(\frac{dm^*}{dt^*}\right) - 1 \quad (3)$$

where $\cos(\gamma)$ and $\sin(\gamma)$ resolve the drag and lift forces from the force normal to the brand's surface. This normal force is constant for a given Reynold number for $-54^o < \gamma < 54^o$ [5], the range over which Eqs. (3) are valid. The normal coefficient, $C_n = 1.17$, is used in lieu of C_d in the equations for L_c and mass loss. Equations (3) collapse to Eqs. (1) for γ=0, and are coupled with position and mass change equations to determine the lofting and propagation path of disk brands with an angle of attack. Note that Eqs. (3) do not require that γ remains constant during the brand's lifetime, allowing the calculation of the flight paths of fluttering disk brands. Mass loss models for disks with $\gamma \neq 0$ and experimental measurements of drag and lift coefficients are the subject of current research.

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Notation

B	Mass transfer number [ ]
C_d	Coefficient of drag [ ]
c_p	Specific heat of air (J/kg K)
g	Acceleration due to gravity [m/s^2]
L	Length [m]
m	particle mass [kg]
$\dot{Q}_o$	Rate of heat release for the fire [kW]
r	Mass consumption number [ ]
t	Time [s]
T_o	Ambient temperature [K]
V	Scalar particle velocity relative to ground [m/s]
W	Vector-valued relative velocity of brand to its surroundings [m/s]
W	Scalar relative velocity of brand to its surroundings [m/s]
x	Propagation distance [m]
z	Vertical height of particle [m]

Greek

α	Thermal diffusivity of air [m^2/s]
γ	Angle of attack from relative velocity vector [ ]
e	Length-to-diameter ratio for disk [ ]
ν	Kinematic viscosity of air [m^2/s]
ρ	Density [kg/m^3]
Φ	Droplet parameter [ ]
Ψ	Disk parameter [ ]

Superscript

*	Dimensionless variable

Subscripts

a	Air
c	Characteristic constant
n	Normal
o	Initial
s	Sphere
x, z	Cartesian coordinate direction